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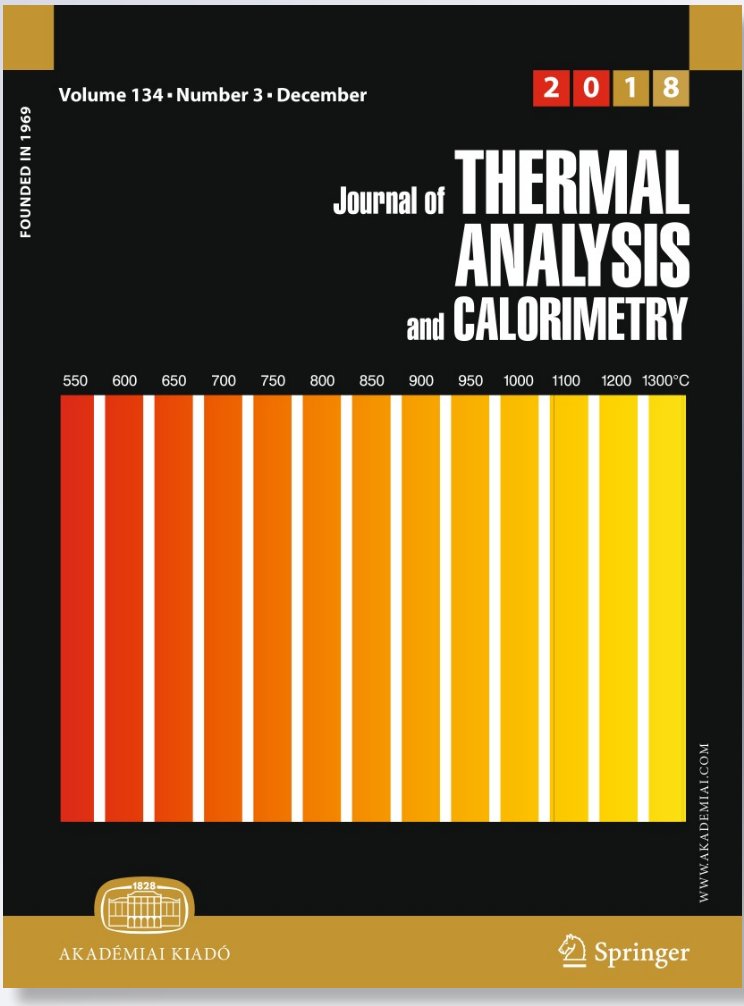

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A review of solar absorption cooling systems combined with various auxiliary energy devices

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Abstract

From both environmental and energy-saving points of view, solar heating and cooling systems have recently proven themselves in the commercial world as the environmentally friendly and sustainable energy systems which can replace the systems powered by conventional sources of energy such as fossil fuels and electricity. In the present paper, the research contributions conducted on solar absorption cooling systems, integrated with different auxiliary energy devices, are comprehensively reviewed and discussed. Also, various cooling systems integrated with solar technologies, i.e., flat-plate collector, evacuated tube collector, compound parabolic collector and parabolic trough collector, are reviewed. The survey and comparison are carried out in terms of some crucial parameters such as coefficient of performance, annual energy consumption and payback period. Further, this work briefly presents and discusses some possible opportunities for future works from the efficiency viewpoint.

Keywords Solar heating and cooling systems · Absorption cooling system · Coefficient of performance · Annual energy consumption · Payback period · Solar thermal collectors

List of symbols

Q	Heat load (kW)
T	Temperature (K)
G_T	Irradiance (W m^{-2})
G_b	Beam irradiance (W m^{-2})
G_d	Diffused irradiance (W m^{-2})
C_R	Area concentration ratio

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Greek symbols

η	Efficiency
β	Inclination of collector (°)
ρ	Ground reflectance

Subscripts

G	Generator
E	Evaporator
amb	Ambient
st	Storage tank
in	Inlet

Abbreviations

SHC	Solar heating and cooling
FPC	Flat-plate collector
ETC	Evacuated tube collector
CPC	Compound parabolic collector
PTC	Parabolic trough collector
COP	Coefficient of performance
SCOP	Solar coefficient of performance
AEC	Annual energy consumption
GWP	Global warming potential
DNI	Direct normal irradiance
SBAC	Solar–biomass hybrid absorption cooling system

GSHP Ground source heat pump
GCHP Ground-coupled heat pump
HTF High-temperature fluid
PCM Phase change material
TES Thermal energy storage
DHD Differential heat of dilution

Introduction

A few years earlier, the prevention of pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO_2) and carbon monoxide (CO) was the main goal of the environmental studies and legal control mechanisms. However, during recent years, controlling dangerous air pollutants such as toxic chemical substances and globally critical pollutants such as carbon dioxide (CO_2) are taken into consideration in the environmental concerns. Meanwhile, the improvement of industrial processes and structures has resulted in some new environmental problems. In 1988, Dincer [1, 2] presented a detailed description of these gaseous and particulate contaminants as well as their impacts on the environment. It is clear that the pollution depends on the energy consumption. In spite of unfavorable effects on the environment by fossil fuel combustion, it is anticipated that the petroleum consumption will reach 123 million barrels until 2025 [3, 4]. The amount of future energy consumption depends on many important factors such as population growth, consumer tastes, economic efficiency and technology developments. In addition, the policies selected by the governments for the energy developments in the world energy markets will play the key roles in the pattern and future energy production and consumption. Now, the evidence implies that by the negligence of the environment, the future of our universe will be impacted negatively. At present, four environmental problems are internationally known: (i) the acid precipitation Iii) the ozone layer depletion (iii) the global climate change and (iv) the global warming potential (GWP). Considering undesirable consequences of using fossil fuels as the most common power source on the environment and its unsustainability as well, employing an alternative renewable energy source could help to reduce and control such irreparable damages to the environment, and save the energy for our future generations. Accordingly, the solar power units, especially the solar heating and cooling (SHC) systems (solar air conditioners and heat pumps), have recently attracted special attention, because the power source (solar energy) is renewable and has no destructive impact on the environment.

In the summer months, the energy demand increases significantly due to the air-conditioning for the high thermal loads and thermal comfort achievement. Some building architectural characteristics like the large ratio of transparent-to-opaque surfaces or building orientation intensify the thermal loads and energy consumption. Since the peak of cooling loads and the maximum available solar power occur simultaneously, applying air-conditioning with solar energy utilization is preferable [3, 4]. There are various air-conditioning technologies in the market which are powered by the solar energy. Among the available solar air-conditioning technologies, a system must be selected which saves primary energy with economic efficiency. Although it is necessary to exploit solar thermal energy with the maximum possible capacity for economic optimization, some additional systems could be employed such as photovoltaic, solar heating and domestic water heating systems.

Solar thermal collectors, as a group of heat exchangers, harness the solar energy to heat up the working fluid. Solar collectors can be applied in many systems or cycles to provide energy. For instance, the compression cycles, absorption cooling and desiccant cooling systems can engage solar collectors as the solar hybrid cooling systems. Due to the high initial costs, solar cooling systems are not competitive with the common cooling systems with conventional power sources (gas-fired or electricity). The cost of solar cooling systems could be reduced by improving their performance and using inexpensive components. The performance improvement leads to a reduction in collector size and production cost. On the other hand, any appropriate combination of solar system and cooling technology may improve the performance of the conventional cooling processes like absorption systems as one of the most favorable methods [5]. In this paper, different cooling systems combined with solar technologies are reviewed and discussed.

Solar cooling technologies

Cooling through absorption cycle has been considered as one of the most beneficial approaches which can be supplied with solar thermal energy. Solar cooling technology related to the absorption systems has been developed commercially so that it was estimated that around 59% of the solar cooling systems in Europe worked based on vapor absorption technology [6, 7]. Three available technologies for cooling purpose which can be linked to solar thermal energy are as follows:

- Absorption systems
- Solid and liquid desiccant
- Solid adsorption

Wilbur and Mitchell [8] studied the effect of different working fluids (such as LiBr/water and NH_3/water as the main working fluids) on the coefficient of performance (COP) for cooling absorption systems. They reported that LiBr–H_2O has the highest COP compared to other working fluids. However, by employing this working fluid, the crystallization occurs at the point of the recuperate discharge into the absorber which will lead to stopping the solution flow inside the device and causes a problem in operation. Considering its low cost and high performance, LiBr–H_2O is a desired candidate for solar cooling purposes. The studies also show that the ammonia/water system possesses the following disadvantages [8–10]:

- Absorption systems with H_2O-NH_3 as working fluid have lower COP in comparison with LiBr–H_2O systems.
- Ammonia-water systems require a higher generator inlet temperature compared with another one. The generator inlet temperature range for a LiBr/water absorption unit should be 70–88 °C, while an NH_3/water absorption unit requires relatively higher temperature range (90–180 °C). Consequently, using flat-plate solar collectors in the NH_3/water cooling systems results in lower COP.
- It needs a higher pumping power because of higher pressure drops.
- It has a more complicated system which requires a rectifier to separate ammonia and water vapor at the generator outlet.
- Due to the cons of using ammonia, there are limitations on the built-in applications of ammonia-based cooling units.

Although H_2O–NH_3 and LiBr–H_2O absorption systems are widely used in all four corners of the world, researchers are still looking for new ones. For instance, De Rossi et al. [11] introduced R21 and R22 as working fluids which are known to have a greater solvability with organic solvents [12]. This ability was investigated using two remarkable solvents (dimethyl formamide (DMF) and dimethyl ether of tetra—ethylene glycol (DMETEG)) [13, 14].

Absorption chillers, which are commercially available for the air-conditioning purposes, usually operate with a mixture of LiBr and water as the working fluid and use steam or hot water as the heat source. In the current review paper, the solar absorption cooling systems using LiBr–H_2O as a hybrid solar cooling technology are investigated in detail.

Solar absorption cooling systems

In general, a vapor absorption refrigeration system is comprised of a condenser, an evaporator, a generator, a pump and an absorber which are collectively capable of compressing the refrigerant vapor. The evaporator produces the vapor refrigerant by separating from the solution using additional thermal energy. The condenser distills the refrigerant, and then, it is expanded by the evaporator [15, 16]. In solar absorption cooling system, the generator of the chiller absorbs heat from the tank attached to the solar collector. Universally, COP as a crucial criterion to evaluate the energetic performance of the absorption cooling systems is defined as follows:

$$\mathrm{COP} = \frac{\text{Cooling load}}{\text{Heat input to the generator}} = \frac{Q_E}{Q_G} \tag{1}$$

The heat input to the generator can be provided by different power source types like renewable (solar), non-renewable energy (fossil fuels) or their hybrid combinations.

According to the regeneration of the solution and thermal operation cycle, the solar absorption systems are classified into the following categories:

- Single-effect.
- Half-effect.
- Multiple-effect (double-effect and triple-effect).

Relatively lower temperatures are needed for the single- and half-effect chillers compared with double- and triple-effect chillers [17]. The triple-effect absorption chillers driven by high-temperature solar thermal collectors have the highest COP. To attain a desired COP, the temperatures of the generator must be more than 150 °C [18] which will result in a higher initial cost [19]. Triple-effect absorption chiller, driven by heliostat and central receiver pair with cascaded cycles and an ejector, is more proper for use in refrigeration cycles with low generator temperature (80–50 °C) [20]. Figure 1 compares the required deriving

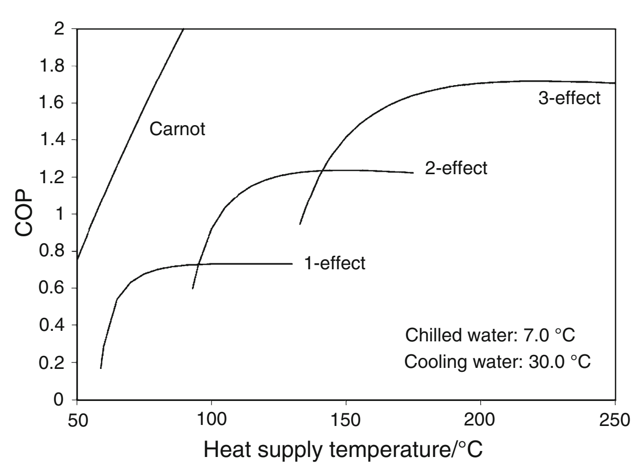


Fig. 1 Variation of COP as a function of solar heat supply temperature for various LiBr–H_2O absorption chiller types [54]. Reprinted with permission from Elsevier

temperatures and COP for single-, double- and triple- effect chillers with the same size components [54]. As it is obvious in Fig. 1, a significant COP increasing is achieved utilizing combination of high-temperature solar collectors and multi-effect absorption chillers. The driving heat source temperature is approximately between 80 to 100 °C for single-effect chillers, while the COP can reach up to 0.7. The generator temperature for double-effect chillers is roughly 100–150 °C, and the COP is limited to 1.4. Eventually, driving temperature range between 180 and 240 °C is required for triple-effect chillers, and the COP can attain a maximum value of 1.8 under the most favorable conditions. With an available high-temperature heat source, employing absorbers with premiere effect leads to higher COP [18]. It was not specified in previous studies whether solar-driven cooling systems based on multi-effect absorption chillers could be competitive owing to their expensive components, tracking and maintenance. On the other hand, as a disadvantage, they operate with only direct normal irradiance (DNI) [21].

Using hot water tank, which has a nearly constant heat input, is an integral part of solar absorption air-conditioning systems [8, 22]. Lof and Tybout [23] reported that the optimum volume of the storage tank is about 50 kg for each m^2 of the collector area. In addition, the range of nominal storage amounts for cooling purposes was improved to 80–200 kg per m^2 of the collector area [24]. For the hot water storage tank, a serious problem is related to heat loss to the peripheral area. Jacobsen [25] estimated 1.65 W/m^2 °C for actual heat loss coefficient which was 50% greater than the previously predicted values. Sometimes the amount of heat dissipation from hot water storage tank may be tantamount to 2 h a day operation of a solar air-conditioning system [26]. In a solar cooling system, a chilled water storage tank may be applied too [27]. Significant heat losses are exerted to the hot water storage tank, while the rate of heat received by the chilled one is lower. The main reason for this is related to a smaller temperature difference between the ambient and the chilled water storage tank. In addition, if the chilled water tank is set up in the right position (close to the air conditioned area), its received heat can assist in cooling. It should be mentioned that the chilled storage may enhance the operational stability as a buffer tank, but it is not able to enhance the system performance in solar cooling.

In general, a parallel configuration of auxiliary heaters is preferred to a series one [27]. A rather high temperature (about 88 °C) is required for the chiller to achieve their maximum performance. Hence, when the temperature in the hot water tank is lower than the required level, an auxiliary heating system is suggested to be directly employed for supporting the chiller. If the auxiliary heater is placed in tandem between the chiller and the hot water storage tank, the temperature of the returned water to the storage tank will be often higher than outlet water. This phenomenon increases the storage temperature and reduces the collector efficiency as well. Nevertheless, a series connection of the auxiliary heater is appropriate when the storage temperature is lower and higher than the required energizing temperature and the received temperature from the generator, respectively. In this way, it supplies the lack of energy to reach the temperature up to the energizing level. This approach may be proper for installations that need auxiliary energy source only for a short time. During the hot season, the hot water used in fan coils of the air conditioners and domestic purposes is directly supplied through the hot water storage tank [10] (Fig. 2).

It is essential to set up an auxiliary energy supplement with solar cooling systems for compatibility with every kind of weathers. As the auxiliary system, the natural gas burners can be employed in order to heat up the inlet water to the generator. Marc et al. [28] stated that designing such an installation and defining the suitable refrigeration capacity of the chiller without considering the backup system is unacceptable. Using a chiller with undersized capacity despite good performance in nominal conditions results in not achieving thermal comfort inside the building during some critical periods of the year. On the other hand, for the same building thermal comfort is always achieved with an oversized chiller which has low performances in nominal conditions. A solar absorption cooling system (single-effect + LiBr/water) was designed and tested in Thailand by Pongtornkulpanich et al. [29]. They illustrated that the ETC used in their system could provide 81% of the thermal energy required for the chiller annually, and the remaining (19%) was supplied using an LPG-fired backup heater. The schematic of this work is represented in Fig. 3. Moreover, the auxiliary energy system may be combined with other source of renewable or clean energy. As it stands, natural gas is the cleanest among all kinds of fossil fuels. It is primarily comprised of methane and has an exothermic chemical reaction with oxygen which produces heat and several chemical byproducts. If the natural gas is combusted, carbon dioxide and water will be produced as the primary byproducts.

Auxiliary clean or renewable energy systems

Most conventional solar cooling systems employ fossil fuels as their backup heat source, and therefore, their gas emission rate and also operating cost are rather high. Biomass energy source was proposed by Prasartkaew and Kumar [30] as a cheaper (or free with considering biomass as a waste material) alternative for an auxiliary heat source for LiBr–H_2O absorption chiller. Their system was named solar–biomass hybrid absorption cooling system (SBAC).

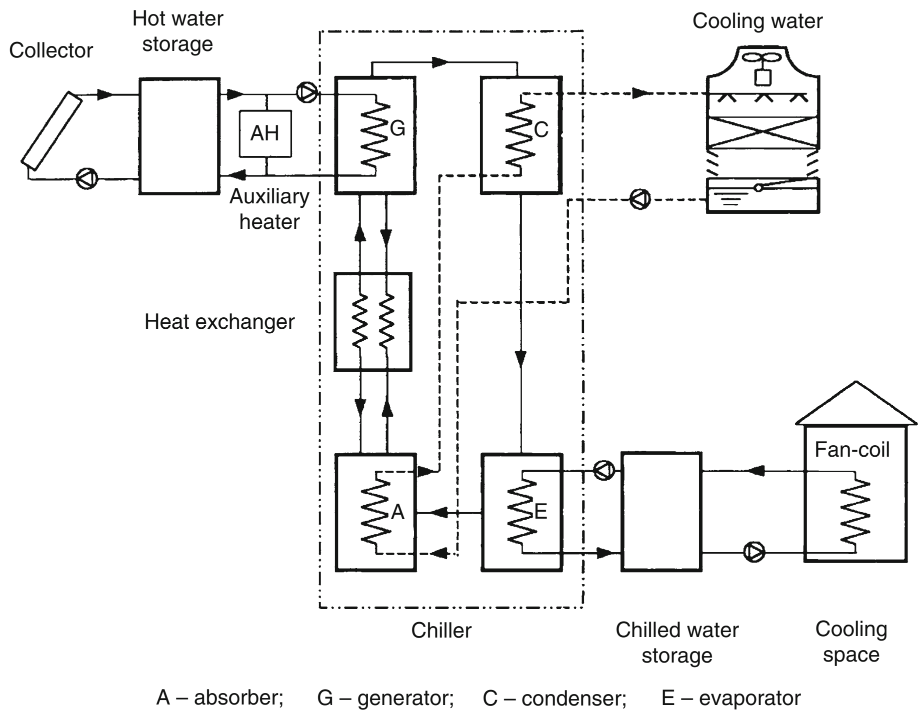


Fig. 2 Schematic of a solar-driven single-effect air-conditioning system [10]. Reprinted with permission from Elsevier

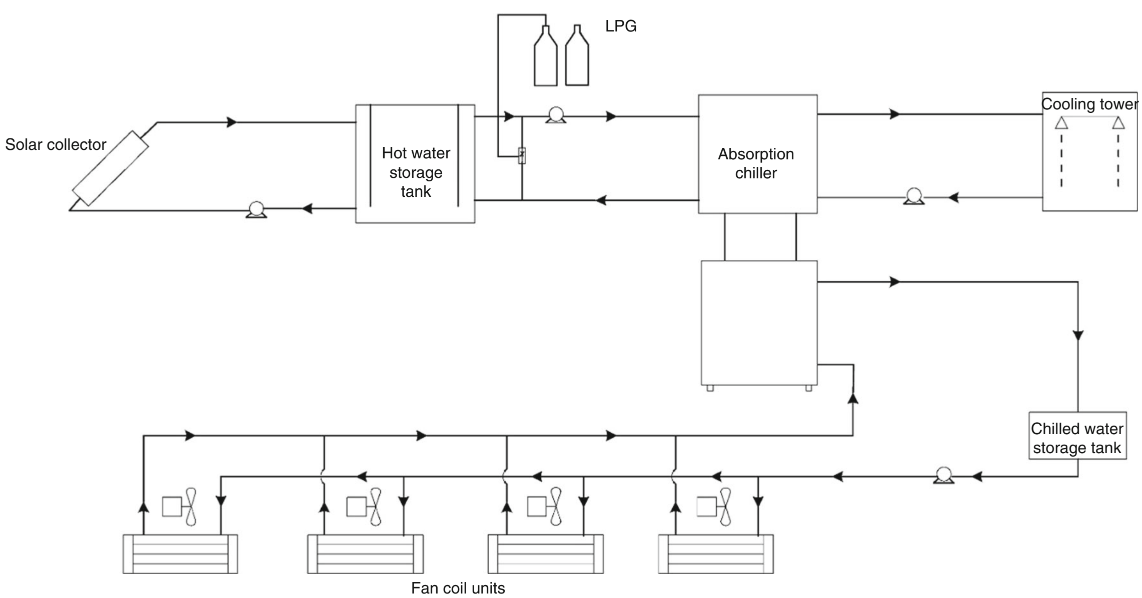


Fig. 3 Schematic of the solar-powered single-effect absorption chiller studied by Pongtornkulpanich et al. [29]. Reprinted with permission from Elsevier

In comparison with the conventional systems, the main difference of their proposed system is biomass-based gasifier boiler instead of fossil auxiliary heat source. Three possible configurations for the solar–biomass hybrid cooling system (see Fig. 4) were investigated in their work:

- Case 1: series configuration of auxiliary heater and the solar water heating system.
- Case 2: parallel arrangement of auxiliary heater and solar collector.
- Case 3: parallel layout of auxiliary heater and the solar water heating system.

All these cases have the same characteristic by which the insulated biomass gasifier boiler has two functions: (i) it acts as an auxiliary source of power when solar energy

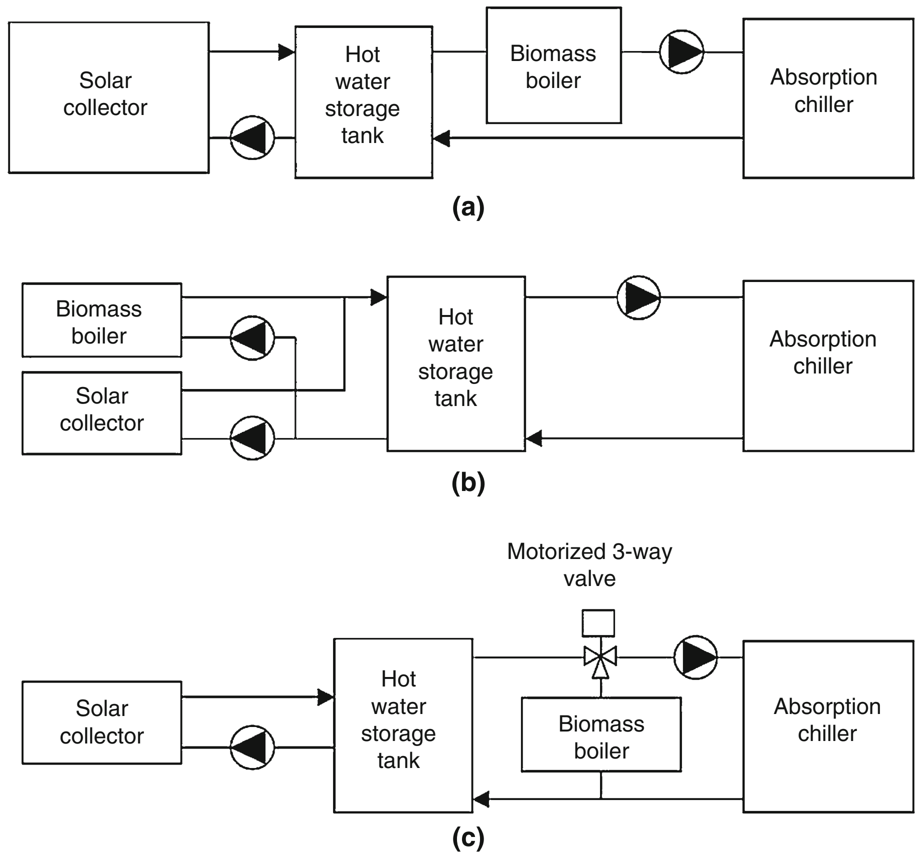


Fig. 4 Possible configurations for the solar-biomass hybrid cooling system studied by Prasartkaew and Kumar [30]. **a** An auxiliary heater is connected in series with the solar water heating system (case 1), **b** an auxiliary heater is connected in parallel with the solar collector (case 2), **c** an auxiliary heater is connected in parallel with the solar water heating system (case 3). Reprinted with permission from Elsevier

is not sufficient to enable the system solely and (ii) it operates as the primary power source in the absence of sunlight. On a clear sunny day, the monthly average daily COP of the system for Case 1, Case 2 and Case 3 is equal to 0.24, 0.29 and 0.48, respectively. If the system is only powered by the auxiliary heater (during the night or cloudy days), Case 3 shows a relatively higher COP rather than the other cases ($\sim$ 0.64). This significant difference between the COP of Case 3 and the other cases can be stored as heat to fulfill heat requirement of the chiller with no need to an external heat source.

For evaluating the consequence of using biomass on the overall economic and thermal performance of the system, Calise [31] analyzed an SHC system in which the gas-fired heater has been replaced with a biomass-fired heater. It was shown that when the solar energy system is designed on the basis of the peak thermal energy demand, there is no remarkable difference between the outcomes for natural gas and biomass as auxiliary fuel. Conversely, using biomass (wood chip) can be considered as the best option for the systems with a smaller solar collector (less area) to achieve an acceptable thermal and economic performance. Li et al. [32] tested a solar absorption cooling system pair with a ground source heat pump (GSHP) as an auxiliary heat source. The chilled water produced by the solar cooling system was stored in a storage tank, and its temperature was kept lower than 18 °C thanks to the ground source heat pump. It could also be turned on during the specific period (22:00 pm to 7:00 am) when the electricity is more inexpensive. The performance of an integrated cooling machine including both free cooling system and solar-powered single-effect LiBr–H_2O absorption chiller was reported by Ahmed Hamza et al. [33]. The system included a cooling absorption chiller (35.17 kW), vacuum tube collectors (108 m^2), a hot water storage tank (6.8 m^3), a cold water storage tank (1.5 m^3) and a cooling tower (134 kW). For sunny, clear sky days, the efficiency of the collectors and COP of the chiller varied from 0.352 to 0.492 and 0.37 to 0.81, respectively. An investigation was carried out by Macía et al. [34] on a novel experimental setup which mainly consists of a solar-assisted absorption ground coupled heat pump (GCHP) and some ETCs. A TRNSYS model has been adopted to examine the effect of generator and condenser temperatures on the performance of the installation regarding the heat pump COP and global efficiency. This effect can be seen in Fig. 5.

A combination of a solar cooling system (single-effect) and a gas-fired cooling system (double-effect) can be employed as a hybrid cooling system based on an absorption chiller. The system works in a solar-driven

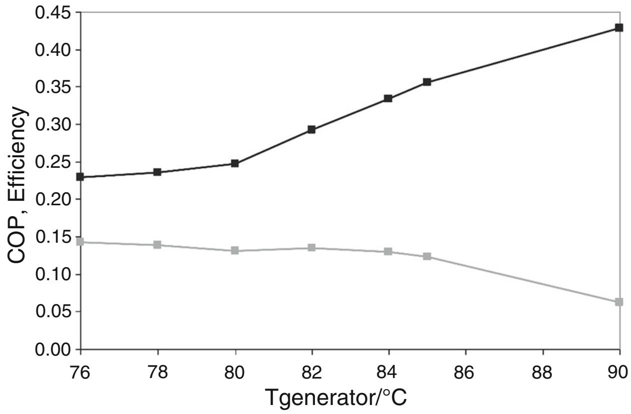
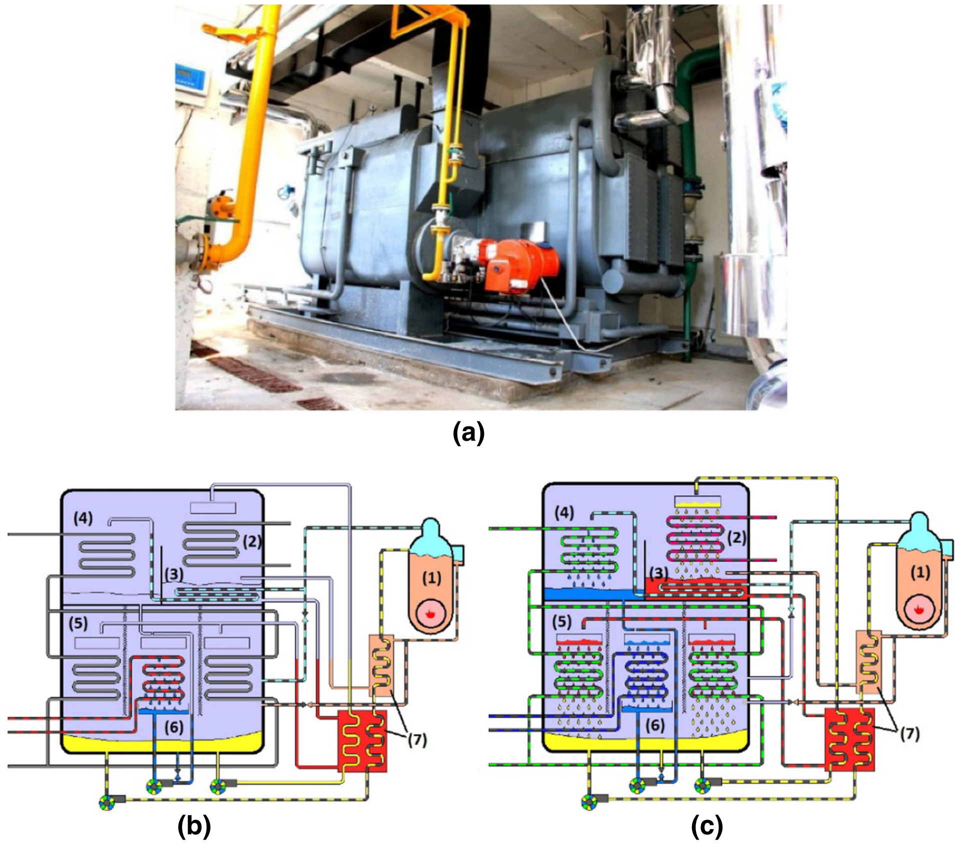


Fig. 5 Variations of global efficiency ( ) and heat pump COP ( ) versus the generator temperature [34]. Reprinted with permission from Elsevier

mode with sufficient solar energy, while the gas-fired heating unit is ready to be used as backup power source. Wang et al. [35] analyzed the operation of the system as mentioned above in a five-star hotel during a year. They reported that gas consumption could be saved about 49.7% for the gas/solar-driven absorption system in comparison with the gas-fired one. Figure 6 indicates the hybrid solar–gas-fired absorption chiller and circulation layout for cooling and heating purpose. The system configuration is illustrated in Fig. 7. The system heat sources consist of the solar collectors (1, 2 and 3), an auxiliary heat source (8) and the gas-fired generator (11). They place on the left side of the diagram. Except for the heat sources, the system also is combined with water tanks (5 and 7), LiBr-water absorption system (11), cooling tower (13), fan coil (12), piping system, pump (4) and control system.

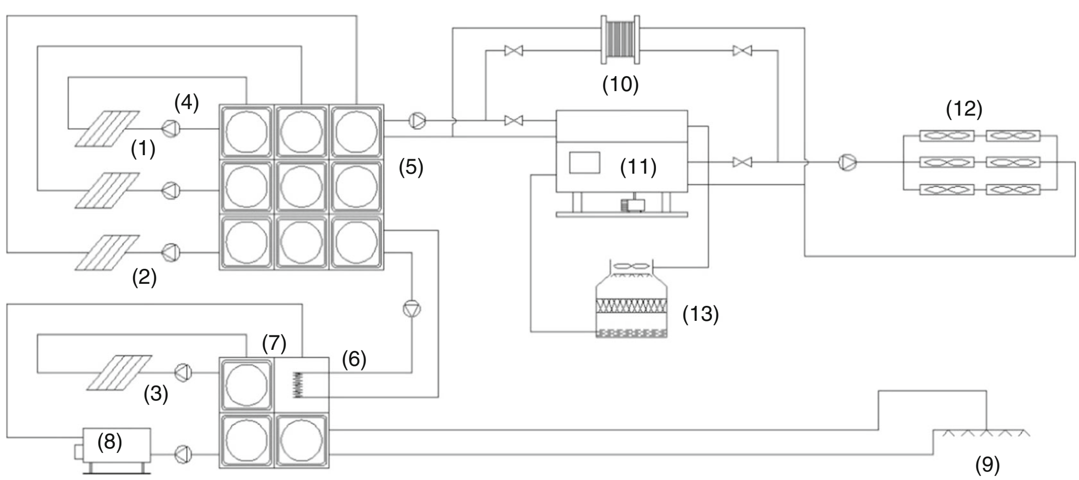
Shirazi et al. [36] investigated the possibility of applying three different LiBr–water absorption chiller types (single-, double- and triple-effect) in vapor absorption SHC systems with common solar thermal collectors. These combinations are briefly presented in Table 1. A schematic diagram of their apparatus is truly illustrated in Fig. 8. They used TRNSYS 17 to simulate each configuration carefully. It was suggested that a 70 L m^{-2} storage volume is enough for SHC1. But for the rest of configurations (SHC2-5), the required storage capacity is 40–50 L m^{-2}. According to the simulation outcomes, if the fraction of DNI is less than 50%, larger collector area will be required for SHC2, SHC3 and SHC5 compared to SHC1. Employing concentrating collector for multi-effect chillers has no preference over solar single-effect chillers in the climates with rather low DNI level. In the climates with DNI fractions above 60%, the smallest solar field is acquired by using SHC5.

A theoretical modeling was carried out by Asfand and Bourouis [37]. They estimated the differential heat of dilution (DHD) using Duhring diagrams. The compositions under study were H_2O/LiBr, H_2O/(LiBr + LiI + $LiNO_3$ + LiCl) with mass composition in salts of 60.16, 9.55, 18.54 and 11.75%, respectively, and H_2O/($LiNO_3$ + KNO_3 + $NaNO_3$) with mass compositions in salts of 53, 28 and 19%, respectively. In absorption cooling systems, such compounds can generally be employed as working fluid. For the mentioned working fluids, a simple polynomial correlation as a function of temperature and concentration of the solution was presented for the obtained DHD data. The proposed correlation could predict the DHD value through analysis of heat and mass transfer for such working fluid mixtures in absorption cooling systems. The results showed that the best DHD is achieved by H_2O/LiBr as working fluid at normal concentration and operating temperature, while the above-mentioned novel working fluid mixtures possess a lower DHD. Bellos et al. [38] investigated the consequence of using an alternative working couple in a solar absorption cooling system. An energetic and exergetic evaluation was performed on the performance of LiCl–H_2O couple in the system and the results compared with the data for LiBr–H_2O as a conventional compound. For feeding the single-effect absorption chiller, FPCs are used in their work. The two compounds were studied parametrically for different heat source temperatures and three ambient temperatures (25, 30 and 35 °C). The maximum exergetic efficiency was attained by using LiCl–H_2O. In another research, Ming et al. [39] analyzed the performance of a single-effect LiBr/water absorption cooling system coupled with parabolic trough collector. The results specified that the chiller could reach its maximum efficiency (instantaneous refrigeration coefficient) which was recorded up to 0.6. Also, for the daily solar heat fraction ranging from 0.33 to 0.41 (in sunny and clear sky days), the daily cooling COP, the chiller and efficiency of the collectors field changes from 0.11 to 0.27, 0.25 to 0.7 and 0.35 to 0.45, respectively. Tzivanidis and Bellos [40] determined the performance of a single-effect H_2O-LiBr absorption chiller pair with a PTC in Athens. A numerical model is developed in order to simulate the system dynamic performance. Some crucial parameters, i.e., mass flow rate and the storage tank volume, were optimized through sensitivity analysis. It was found that the system COP is a function of the load temperature, so that COP shows a significant enhancement ($\sim$ 70%) by rising the load temperature from approximately 97–105 °C. Although COP of the system increases evermore with an increment of load temperature, COP improvement will not be very considerable for the temperatures higher than 105 °C.



1-gas boiler (high pressure generator), 2-low pressure generator for single effect circulation, 3-low pressure generator for double effect circulation, 4-condensor, 5-absorber, 6-evaporator, 7-solution heat exchanger

Fig. 6 **a** Hybrid solar–gas-fired absorption chiller; **b** Circulation chart for cooling; **c** Circulation chart for heating [35]. Reprinted with permission from Elsevier



(1) Evacuated tube gravity heat pipe solar collector, (2) Evacuated tube horizontal heat pipe solar collector, (3) Evacuated glass tube solar collector, (4) Pump, (5) Water tank for air conditioning, (6) Cooper pipe heat exchanger, (7) Hotel hot water tank, (8) Auxiliary boiler, (9) Hot water use, (10) Plate heat exchanger, (11) Absorption chiller, (12) Fan coil, (13) Cooling tower

Fig. 7 Schematic diagram of the hybrid energy system investigated by Wang et al. [35]. Reprinted with permission from Elsevier

Table 1 Configurations of the systems studied by Shirazi et al. [36]

System	Name	Configurations
Single-effect chiller	SHC1	ETCs
Double-effect chiller	SHC2	PTCs
	SHC3	Linear Fresnel micro-concentrating collectors
	SHC4	Evacuated flat-plate collectors
Triple-effect chiller	SHC5	PTCs

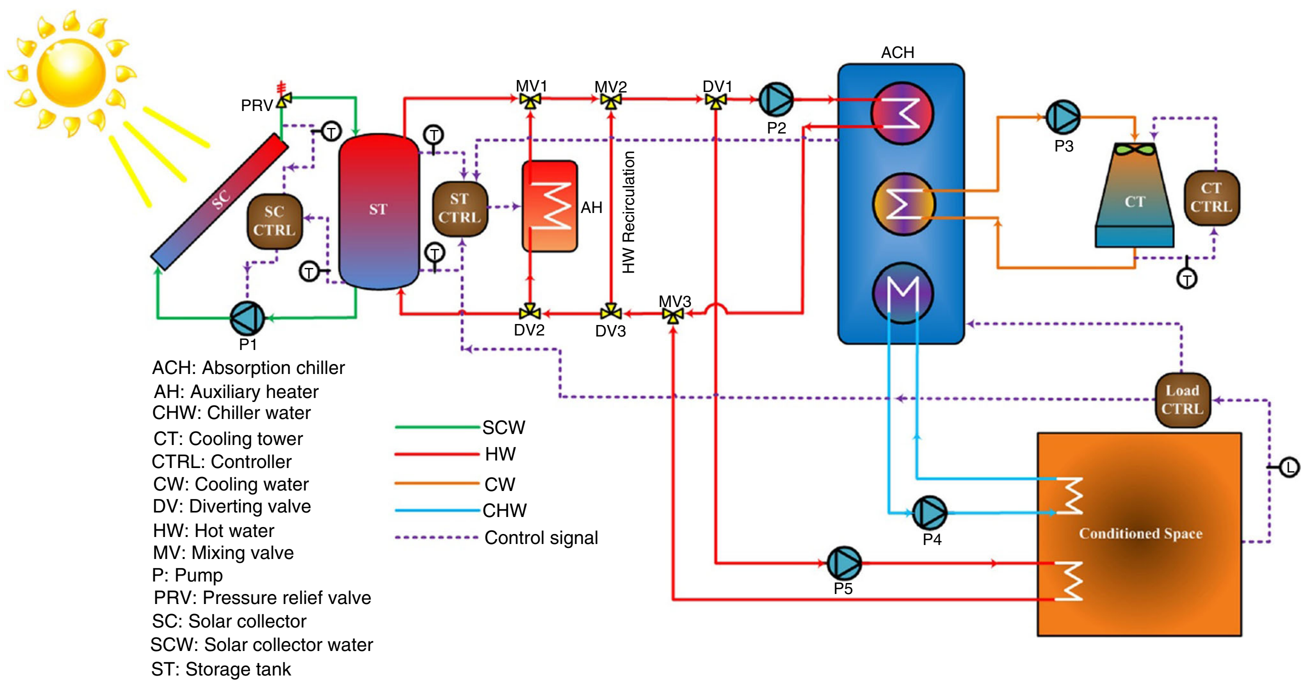


Fig. 8 Schematic of an SHC absorption chiller layout [36]. Reprinted with permission from Elsevier

Solar technologies

In general, solar energy collector is namely a device that absorbs the incoming solar radiation which transforms into heat and then transfers to a fluid (commonly air, water or oil) flowing through the collector. In order to provide thermal energy, solar collectors can be widely utilized as a heating source in solar absorption cooling systems. Water saving, maintenance costs and space can be counted as advantages of using solar collectors instead of cooling towers [58]. Two solar collector types are mainly available: concentrating and non-concentrating (stationary). In a non-concentrating collector, the intercepting area for solar radiation and absorbing one are the same. A sun-tracking concentrating solar collector contains some concave reflecting surfaces to intercept and concentrate the sun-beam radiation to their focus which leads to increment the radiation flux. There are various types of solar collector available in the market such as flat-plate collectors (FPC), evacuated tube collectors (ETC), compound parabolic collector (CPC) and parabolic trough collector (PTC). In this section, regarding the previous works available in the literature, the appropriate types of collectors for absorption cooling systems are investigated.

FPCs are the most prevalent for its application in solar domestic water heating systems as well as solar space heating. A schematic diagram of a domestic solar water heating system (using FPC) pair with an electric resistance heater as an auxiliary energy source is shown in Fig. 9 [61]. A conventional FPC is comprised of a metal box which is precisely insulated and composed of a glazing cover (glass or plastic) and a dark-colored absorber plate. FPCs are usually applied for low-temperature applications (up to 100 °C). It should be noted that some new collector types which employ vacuum insulation may show slightly higher efficiency [41]. Owing to the highly selective coatings, an actual standard FPC may attain high stagnation temperatures (above 200 °C). Selecting such collectors helps us to reach gracious efficiencies at the temperatures about 100 °C. These collectors can heat up liquid or air at the temperatures below 80 °C.

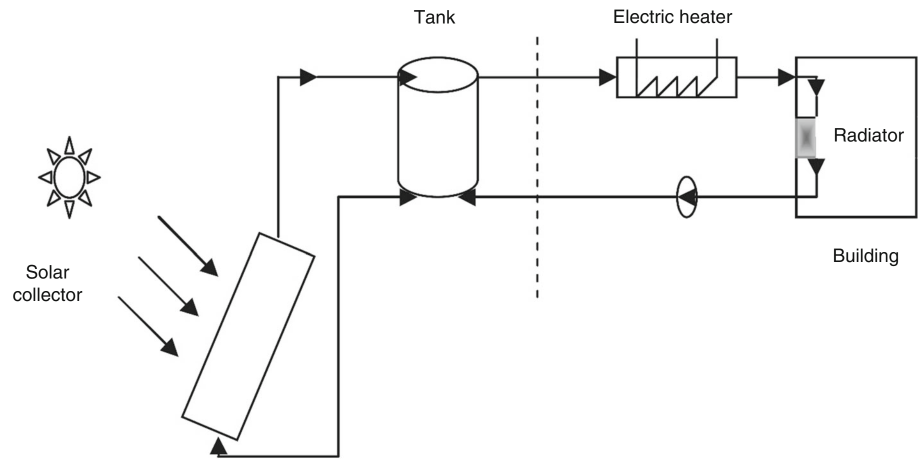


Fig. 9 Schematic diagram of a solar domestic water heating system [61]. Reprinted with permission from Elsevier

CPCs can collect incident ray within the specified scope by the ideal concentration ratio onto the receiver. The potentials of such solar collectors have been discussed by Winston [42] in detail. CPCs can absorb incoming radiations with a relatively wide range of angles. Through using multiple internal reflections located at the bottom of the collector, any inlet radiation to the orifice with the collector acceptance angle is guided to the absorber surface. CPCs have been designed in two basic types so far: the symmetric and the asymmetric. Two main absorber types (tubular absorbers and fin type with pipe) are usually applied to CPCs [43].

Evacuated heat pipe solar collectors which abbreviated as evacuated tube collectors (ETCs) possess vacuum-sealed tubes which consist of heat pipes. Through ETCs it can be observed that combining a selective surface and an effective convection suppressor leads to excellent performance at high temperatures. This vacuuming procedure decreases convection and conduction heat transfer losses and enables the collectors to operate at higher temperatures compared to FPCs. But they can collect all incident beams in direct and diffused form in the same manner as FPCs. However, their efficiencies depend on the beam angle of incidence (higher efficiencies within low incidence angles). Therefore, ETC is preferred to FPC in day-long performances. A tube is aligned at the focus of a parabolic concentrator in the ETC collector which includes a metallic absorber surrounded by an evacuated glass-housing. This tube is applied to transfer the solar beam irradiation which is reflected by the parabolic concentrator to the inside high-temperature fluid. These collectors can only transform a fraction of the total irradiation which is partly related to small thermal losses at the external surface of the tube. This heat transfer surface is typically small in comparison with the total aperture area. Moreover, ETCs could be equipped with a single axis tracking system for keeping the solar incidence angle in an acceptable range. Depending on collector classification and tracking systems, various possible configurations are available with different efficiencies as follows [31]:

1. Horizontal collectors with NS axis orientation and tracking system following the solar azimuth angle
2. A horizontal collector with EW axis orientation and tracking system following the solar zenith (also called "altitude") angle.

Since the annual solar gain of the first one is more, it is preferable for summer operation and solar heating–cooling applications [44, 45].

PTC is probably the most favorable technology of concentrating solar collectors [31] which its output temperature may rise even higher than 500 degrees. A superheated substance such as water, oil (i.e., diathermic oil), steam or molten salts can be applied as the high-temperature fluid (HTF) in this system [46]. Space occupation and large size are known as disadvantages of typical PTCs (e.g., the orifice and the length of a Luz LS3 were 5.7 and 99 m, respectively). However, several new PTCs with small collectors have been recently manufactured (e.g., Solitem PTC 1800, with orifice and length of 1.8 and 5.09 m, respectively). Generally, the main purpose of recent researches on PTCs is augmenting their efficiency and also decrement of capital cost which leads to fabricate more compatible rooftop solar collectors in terms of size [47].

To use various solar collector types independently or combined with other energy systems, it is vital to select a solar collector with high performance and efficiency which fits to the desired application. For this purpose, it is necessary to determine the efficiency curve for the solar collector in terms of solar radiation, ambient temperature and inlet temperature. Equations (2–7) can be used to determine the thermal efficiency of various collector types:

- For an FPC [62]:

$$\eta_{\mathrm{FPC}} = 0.75 - 0.5\left(\frac{T_{\mathrm{FPC,in}} - T_{\mathrm{amb}}}{G_{\mathrm{T}}}\right) \tag{2}$$

where G_T, as the radiation on the tilted surface, is calculated by the Liu & Jordan model [63]:

$$G_{\mathrm{T}} = R_{\mathrm{bm}} \cdot G_{\mathrm{b}} + G_{\mathrm{d}}\left(\frac{1+\cos\beta}{2}\right) + (G_{\mathrm{b}} + G_{\mathrm{d}})\left(\frac{1-\cos\beta}{2}\right) \cdot \rho \tag{3}$$

- For a CPC with 1.12 concentration ratio [64]:

$$\eta_{\mathrm{CPC}} = 0.7 - 3.4\left(\frac{T_{\mathrm{CPC,in}} - T_{\mathrm{amb}}}{G_{\mathrm{CPC}}}\right) \tag{4}$$

where G_{CPC}, as the radiation which is exploited by CPC, is given as [65]:

$$G_{\mathrm{CPC}} = G_{\mathrm{T}} - G_{\mathrm{d}}\left(1 - \frac{1}{C_{\mathrm{R}}}\right) \tag{5}$$

- For an ETC [66]:

$$\eta_{\mathrm{ETC}} = 0.82 - 2.19\left(\frac{T_{\mathrm{ETC,in}} - T_{\mathrm{amb}}}{G_{\mathrm{T}}}\right) \tag{6}$$

where G_T has been given in Eq. (3).

- For a PTC with the concentration ratio ranging from 14 to 15 [59]:

$$\eta_{\mathrm{PTC}} = 0.762 - 0.2125\left(\frac{T_{\mathrm{PTC,in}} - T_{\mathrm{amb}}}{G_{\mathrm{b}}}\right) - 0.001672 \cdot \mathrm{G_b} \cdot \left(\frac{T_{\mathrm{PTC,in}} - T_{\mathrm{amb}}}{G_{\mathrm{b}}}\right)^2 \tag{7}$$

Since single-effect LiBr/water absorption chillers are powered by regular commercial FPCs or ETCs, they are beneficial regarding the operating temperature range of driving thermal source. Hence, the majority of solar cooling systems work based on single-effect LiBr/water absorption chillers. Generally, these machines require driving heat temperature ranging from 80 to100 °C and can achieve a COP of around 0.7 under a normal operating condition. The range of COP for the LiBr/water cooling cycles (half-effect) is estimated from 0.3 to 0.4. In water-cooled systems, driving temperature is typically in the range of 60–70 °C, while on average, it is 25 °C higher in air-cooled conditions. Kim et al. [48] have theoretically investigated the feasibility of applying a heat-coupled parallel flow absorption cycle (half-effect) for a low-temperature-driven air-cooled LiBr/water absorption chiller. This analysis was carried out for a solar air-conditioning system using flat solar collectors in hot weathers condition. They showed that the direct and indirect air-cooled chillers could provide chilled water at 5.7 and 7.8 °C with rather the same COP, respectively. The experiments were accomplished on the hot water at 90 °C under various ambient temperatures (35 and 50 °C). Although rising ambient temperature from 35 to 50 °C results in a decrement of COP and cooling power for both types of air-cooled chillers (direct and indirect), these reductions are relatively higher for the direct one. The effect of ambient temperature on COP of direct and indirect chillers is illustrated in Fig. 10.

Experimental and simulation-based studies were done by Florides et al. [49] to evaluate the performance of a domestic solar absorption (H_2O–LiBr) cooling system. It was indicated that cooling requirement of a well-insulated housing in Nicosia, Cyprus, can be met through a system with COP equal to 0.74. The system was integrated with CPCs in which curved reflectors are used to concentrate radiations onto a small absorber area. For higher water temperature applications, CPCs are preferable compared to FPCs. This concentrating collector performs appropriately in direct sunlight. But in case of cloudy or hazy skies, it has not a desirable operation due to a few rays captured and reflected onto the absorber. For the climates with a high amount of direct solar radiation like Cyprus, stationary concentrating collectors are the best choice. Despite 20% higher efficiency of ETC rather than FPC (at output temperature ranging from 80 to 90 °C), its cost is about 40% more. Hence, Prasartkaew and Kumar [30] chose FPC for their system. Regardless of installation area, the FPCs are more cost-effective, inexpensive (in terms of maintenance and operating), simple and architecturally adaptive than

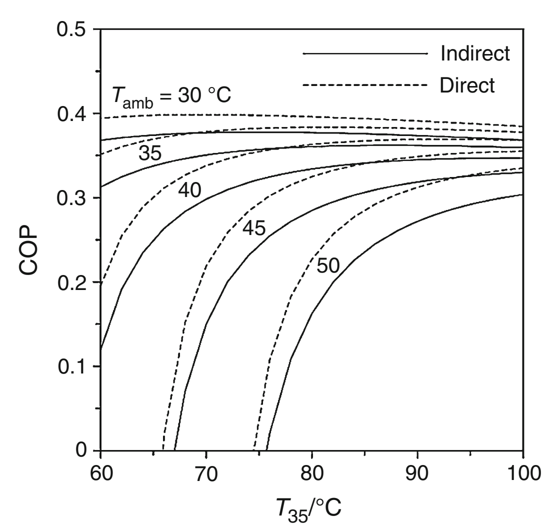


Fig. 10 The effects of ambient temperature on the performance of air-cooled LiBr/H_2O absorption chillers (half-effect) [48]. Reprinted with permission from Elsevier

ETCs [55]. With improved performances as well as reduced costs, concentrating collectors may become noteworthy in the future [30]. High-temperature solar collectors such as PTCs should be selected for use in solar cooling systems based on multiple-effect absorption chillers. Qu et al. [45] installed and tested a solar-driven absorption cooling system (double-effect) at Carnegie Mellon University. The system employed linear parabolic trough solar collectors with 52 m^2 area, a 16 kW double-effect LiBr/water absorption chiller and a heat recovery exchanger. The absorption chiller was a dual-fired and integrated with a cooling tower. Its regenerator included a natural gas-fired heater to power the system when solar energy was insufficient. In their trial, a significant portion of the useful solar energy (see Fig. 11) was used to preheat the system because of its large thermal heat capacity and the heat losses at night.

Tierney [50] studied some high and low-temperature SHC systems for different climates. It was represented that the maximum saving ($\sim$ 86%) is attained through the integration of double-effect absorption chillers and PTC. In order to perform an economic feasibility study on the systems, it was simulated without considering any building or cost model. Ghaith and Razzaq [56] numerically investigated the energy and environmental performance of a double-effect absorption chiller combined with PTC for cooling purpose of a four-storey building in Dubai. In their experiments, a bio-heating unit was employed as an auxiliary heat source in the absence of sunlight. They also carried out comparative studies against an alternative renewable system comprised of single-effect absorption chiller pair with FPC [57] and the conventional electrical system in terms of environmental and economic impact. Operating their proposed renewable system (double-effect absorption + PTC) causes both annual energy consumption (AEC) and operational costs to be significantly diminished. For instance, it results in 519,322 kWh savings of annual energy consumption as well as 2.49 years payback period which is rather low compared to that of the alternative renewable system ($\sim$ 4.98 years). In some previous works, parametric studies were performed on solar cooling absorption systems powered by various types of the solar thermal collector (PTC, ETC) in two cities with rather different situations in terms of sunlight level in Iran (Ahvaz and Tehran) [51, 60]. An innovative SHC system was presented by Calise [31]. A dynamic model was applied based on the integration of a double-effect LiBr–H_2O absorption chiller and PTC. A biomass heating unit was used as an auxiliary power source for both heating and cooling. Owing to unavailability of concentrating solar collectors in the commercial world, the full development of this technology is currently confined, and it is still an emerging technology. Sun et al. [35] used four groups of solar collectors (see Figs. 7, 12). The three major groups of solar collectors with 1020 m^2 total area included (i) horizontal heat pipe and (ii) gravity-assisted heat pipe ETCs which utilized 4950 and 1425 pipes, respectively. These three solar collector groups provided the hot water needed for the heating loop of the absorption chiller. The thermal efficiency related to the application of solar collectors was carefully investigated. For heating purposes of the solar collectors, thermal efficiency was up to 65%, while if the hot water supplied the chiller, thermal efficiency dropped by 20–25%. Furthermore, the fourth group of heat pipe type evacuated glass tube collectors with 750 tubes, and around 120 m^2 area was only offered to supply hot water demand of the hotel.

Bellos and Tzivanidis [52] studied a solar cooling system in which solar collectors coupled with single-effect LiBr/water absorption chillers. The cooling demand was 100 kW at 10 °C for Athens in summer. Four different types of collectors (FPC, ETC, CPC and PTC) were tested and compared in this research. For each system, the minimum collecting area was determined through an exergetic optimization. Results showed that ETCs are the most beneficial technology. Although the system using PTC is

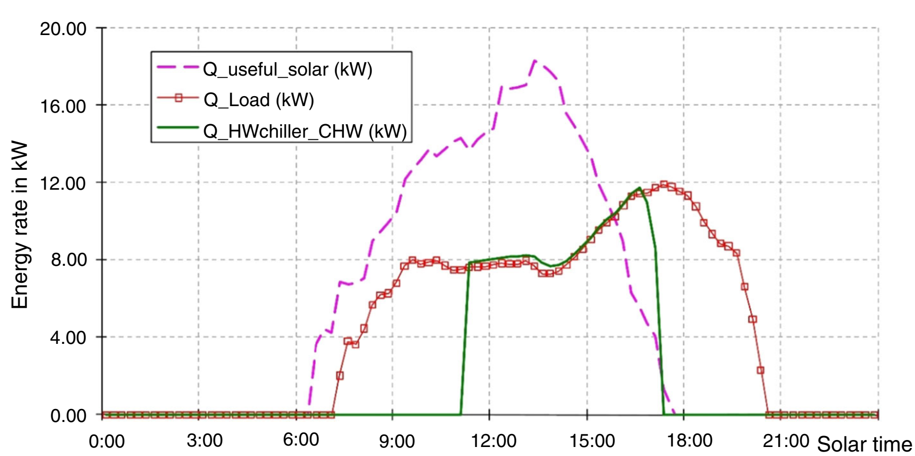


Fig. 11 Useful solar energy, cooling load, and cooling provided by chiller on a specific day [45]. Reprinted with permission from Elsevier

Fig. 12 Solar collectors in the system studied by Sun et al. [35]. Reprinted with permission from Elsevier

the most optimal in terms of exergy delivery, its high capital cost makes it an illogical selection. The collector efficiency depends on the operating conditions. As a critical parameter in the system, water inlet temperature is related to the temperature of the heat source ($T_{s,in}$). Figure 13 presents the influence of heat source temperature on the efficiency of different collector types. As can be observed, there is an indirect relationship between the efficiency of the collectors and heat source temperature. It is also seen that PTC is the most efficient of all types.

In another similar work, Pandya et al. [59] economically and thermodynamically compared the performance of single-stage absorption cooling system (NH_3–water) pair with various types of solar thermal collectors in the city of Mehsana, India. According to their findings, heat source temperature has a substantial effect on the system performance parameters. They also found that performance of solar absorption systems decreases as ambient temperature rises which can be attributed to the reduction of the solar coefficient of performance (SCOP). Comparing the performance of the absorption cooling system combined with ETC and FPC, it was observed that the ETC-based system is superior from the thermodynamic and economic viewpoint. However, comparison of the performance for the system integrated with PTC, ETC shows that PTC-based system has marginally higher thermodynamic performance, while it requires relatively higher collector area and as a consequence production cost. Figure 14 clearly illustrates the influences of heat source temperature ($T_{st,in}$) on SCOP of the cooling system pair with different solar thermal collectors. Through evaluation of key performance indicator, the absorption cooling system (NH3–H2O) driven by ETC was thermodynamically and economically distinguished as the most optimal of all.

Acuña et al. [53] presented the performance of a diffusion absorption cooling system which employed a CPC as the heat source. They investigated the effect of several working fluids on the performance of the mentioned system. $LiNO_3$ (Lithium nitrate) and NaSCN (sodium thiocyanate) absorbent substances and NH3 (ammonia) as the refrigerant were used for the cooling system. $C_3H_8O_3$–H_2O (Glycerol/water), $C_2H_6O_2$–H_2O (ethylene glycol/water) and $C_3H_8O_2$–H_2O (propylene glycol/water) were used as heat transfer fluid between the CPC and the cooling system. They showed that the best COP is estimated for NH_3–$LiNO_3$ working mixture and $C_3H_8O_3$–H_2O heat transfer fluid compared to the other heat transfer fluids. Their test section is illustrated in Fig. 15.

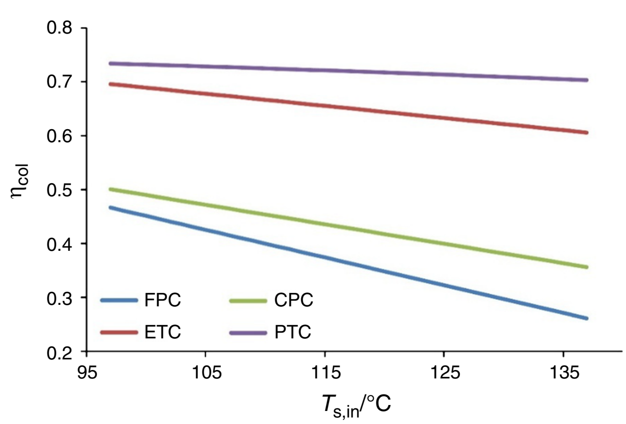


Fig. 13 The efficiency of collectors as a function of heat source temperature level [52]. Reprinted with permission from Elsevier

Future works

Apart from being sustainable and eco-friendly, the current solar-powered cooling systems are still not competitive with the conventional cooling systems in terms of efficiency. Hence, it is needed to find practical solutions to

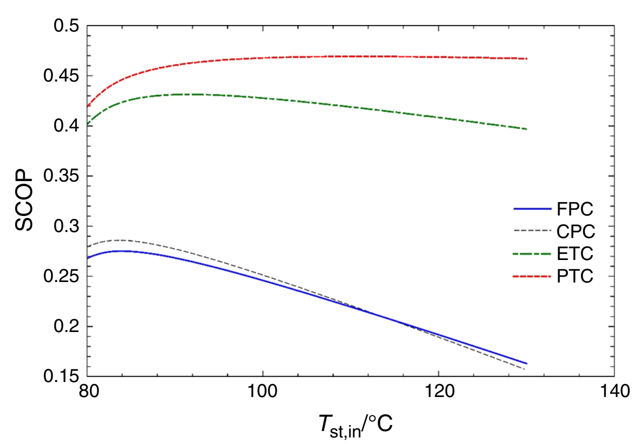


Fig. 14 Variation of SCOP against heat source temperature for a cooling system pair with various collector types [59]. Reprinted with permission from Springer Nature

Fig. 15 A photograph of the test section (compound parabolic concentrators with concentric tube absorber) studied by Acuña et al. [53]. Reprinted with permission from Elsevier

improve their performance. Employing nanofluids (conventional or hybrid) in solar thermal collectors as promising heat transfer fluids can be counted as one of these solutions. So far, many scholars have worked on the performance of different solar collector types using such heat transfer liquids [67]. Despite their improved thermophysical properties (thermal conductivity) which make them more proper for the heat transport applications, using nanofluids is still challenging due to some certain problems such as high cost, instability, pressure drop and corrosion of components, and needs further investigations. Azizi et al. [68] recently fabricated and characterized a highly stable aqueous copper/carbon dot (Cu/CD NHs) nanofluid via a facile precipitation method through a disproportionation reaction. Their proposed nanofluid showed no sedimentation after a month being in a stationary state. Utilizing such novel nanofluids in solar thermal collectors can be an interesting proposal for future work. As another solution, using phase change materials (PCMs) and nanoencapsulated phase change materials (Nano-PCMs) for thermal energy storage (TES) in SHC systems can help to attain higher efficiency. The application of PCM solar collectors and PCM storage tanks in SHC systems is still in its preliminary steps which need to be studied scrupulously. Finally, performing feasibility and performance evaluations on the integration of SHC systems and other renewable energy sources, i.e., wind power, geothermal, tidal power and so forth, can be taken into account as future research topics.

Besides the proposed items, the following works are worthy to do for future studies:

- Conducting more experimental studies by making hybrid setups.
- Conducting scale-up for the hybrid units and making them possible for commercialization.
- Economic analyses are vital for such systems. Also, exergy and exergoeconomic studies are recommended.
- Since these systems are utilized and made as a hybrid, optimization is necessary to find the best solution for their configurations.

Conclusions

Hybrid solar cooling systems which consist of cooling cycles and solar energy (green energy) technologies are appropriate for high capacity absorption/adsorption systems as well as lower capacity compression systems. In addition to the significant reduction in pollution by using such cooling systems, proper integration of the solar technology and the cooling cycle can considerably improve the performance of conventional systems, especially the absorption one. This paper reviewed and summarized the research contributions conducted on solar absorption cooling systems integrated with various auxiliary energy devices. Some conclusions can be listed as follows:

- Triple-effect absorbers with an available high-temperature heat source have the highest COP within multi-effect absorption chillers. But solar-driven multi-effect absorption chillers have expensive collectors, pipework, tracking and maintenance.
- For different SHC layouts, all studies pointed out that an appropriate selection of efficient auxiliary heating and cooling units as well as storage tanks must be taken into account during the design process. It is necessary to embed auxiliary energy sources (backup heating unit) to supply solar-driven cooling systems for all-weather operation. Further, other options of clean or renewable energies could be employed as the auxiliary energy source for solar cooling systems. In addition, storage tank could improve operational stability as a buffer tank.
- The FPCs are more simple, cost-effective, inexpensive (in terms of operation and maintenance costs) and architecturally adaptive in comparison with other configurations. The cooling system with CPCs needs small absorber area, and for higher water temperature applications, FPCs are more preferable.
- It can be summarized that high-temperature SHC combined with multiple-effect absorption with PTCs may be considered as one of the most beneficial renewable energy technologies for cooling purpose in public buildings (such as universities, hospitals and educational buildings). However, there are some limitations of using PTCs such as commercial unavailability or high initial cost. On the other hand, the single-effect absorption cooling system using LiBr/water as

working couple can be properly selected for domestic solar purposes. Applying such system or a high-temperature SHC system integrated with FPCs and ETCs can be more reliable and economical. It is noteworthy mentioning that in day-long performances ETC is preferred to FPC.

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